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High Concentrator PhotoVoltaics efficiencies: Present status and forecast

P. Pérez-Higueras, E. Muñoz*, G. Almonacid, P.G. Vidal

Center of advanced studies in Energy and Environment, IDEA Research Group, University of Jaén, Campus Las Lagunillas, Jaén, Spain

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ABSTRACT

Photovoltaic devices are in a mature technological stage with a long and wide field experience; but if this source of energy wants to compete against other renewable energy sources or even to get into the traditional energy generation system, it is necessary a novel scientific progress in the behavior of these photovoltaic systems. In this challenge is where High Concentrator Photovoltaic technology can have a main role, as it has proved, in the last researches published, to have the potential to achieve high levels of energy conversion performance. In this paper, it is described a brief summary of the CPV state of the art, as well as it is forecast some efficiencies values up to 2015, where a CPV module could reach 40% of efficiency, while the global CPV system could achieve approximately a 32%.

Contents

1. Introduction

The Concentrator PhotoVoltaics (CPV) is based on the use of optical devices that increase the light received on the solar cell surface. The idea is simple: optical devices with cheap and easily available technology (lenses and mirrors) are used to concentrate the light on small and high efficient photovoltaic solar cells. The final goal of the CPV systems is to reduce the cost of the electricity produced by means of replacing the cell surface (expensive material) with cheaper optical devices [1].

It is usual to classify the CPV systems according to the concentration ratio of the solar radiation incident onto the cell. This ratio indicates the number of times that the solar light is concentrated and it is usually known as 'Suns'. According to that description, it can be defined three different CPV systems:

- Low Concentration (LCPV): it refers to those systems that concentrate the light between 1 and 40 times (1–40×), so the LCPV systems have a concentration factor between 1 and 40 suns.
- Medium Concentration (MCPV): these are the systems that concentrate the sunlight between 40 and 300 times (4–300×)
- High Concentration (HCPV): the concentration level of these systems varies between 300 and 2000 suns (300–2000×)

This report will be exclusively focused on High Concentrator PhotoVoltaics systems (HCPV), owing to the following reasons:

- Most of the companies are investing in this technology
- These systems are the one with more power installed of the CPV technology
- HCPV systems are based on a technology that in a short-medium term will reach a higher trajectory in terms of efficiency and energy production
- It has the best perspectives on costs reduction

2. HCPV technology description

A HCPV system is a PV system composed of a collection of HCPV modules electrically interconnected, and the *Balance of System* (BOS). A HCPV module is the smallest, complete, environmen-

* Corresponding author. Tel.: +34 953213306.
E-mail address: emunoz@ujaen.es (E. Muñoz).

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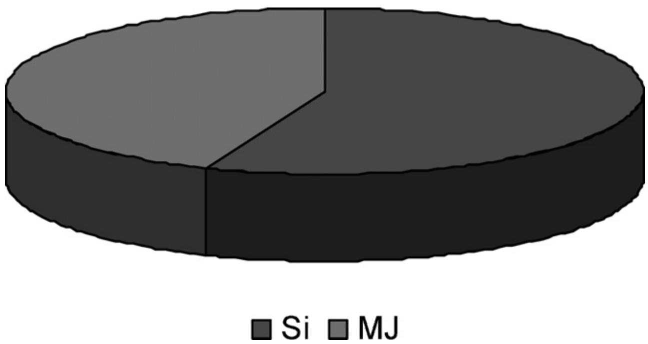

Fig. 1. Distribution of the cell technology used in HCPV modules until 2009.

tally protected assembly of cells and optical devices that is able to transform an input of unconcentrated solar radiation into electrical energy. Consequently, a typical HCPV module is made up of a group of cells, primary and optionally secondary optics and the housing components [2–4]. The BOS includes any tracking mechanism, support structures, external wiring and connection boxes, as well as inverters, other power conditioning devices and data acquisition equipment.

Nowadays, a HCPV module is composed of two different kinds of solar cells: high efficiency silicon and multijunction photovoltaic cells. These last devices have a similar mechanism of electricity conversion as the Silicon ones, but the efficiency of solar conversion into electricity is higher, which means a significant increase in the potentiality of electricity production. The reason of these high efficiency levels has its explanation in the better use of the sunlight energy, as these multijunction cells are capable of being more sensitive to a wider spectrum of the incoming sunlight. This sensitivity is achieved by means of the implementation of several layers of different materials with a specific band gap, so its material reacts to a particular range of the solar spectrum. When these layers are stacked together, the final result is a photovoltaic cell that can absorb most of the solar spectrum range, and it is not limited to a specific range, as it happens with Silicon solar cells. The number of layers of the present multijunction cell is three, although recent researches are going in the direction of an increment of layers.

In Fig. 1 it is displayed the percentage of the cell technology used in HCPV. The reason of the greater incursion of Silicon cells in HCPV is based on the systems that are currently being installed, where a company has several megawatts made of silicon cell modules, but nowadays all the HCPV companies are moving towards multijunction cells.

These multijunction cells are still in an emergent commercialization stage, far away from the level of industrialization of Silicon ones, but there are many research centers that are making a big effort in the development of these cells. Among these centers, it is outstanding the Fraunhofer-Institut for Solare Energyessystem, The Ioffe Physical-Technical Institute, The National Renewable Energy Laboratory or the Instituto de Energía Solar of the Universidad Politécnica of Madrid.

The implementation of PV systems with multijunction solar cells would not be profitable, in economic and energy terms, without the use of devices that concentrate the sunlight onto the cell surface, so in HCPV systems it is a must to place optical devices in the module with a double purpose:

- To rise up the sunlight flux available on the cell surface so it can generate more output energy
- To replace the most expensive part of a CPV system, which it is the multijunction solar cell, with cheaper plastic optical devices

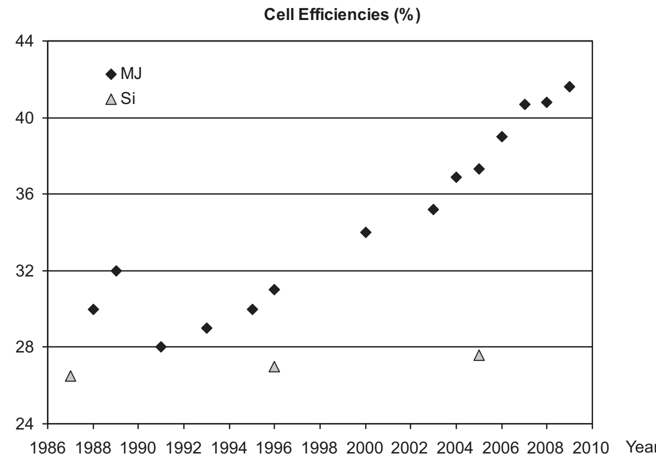

Fig. 2. Efficiency evolution of multijunction and silicon solar cells.

According to the concentration ratio used to classify the CPV systems described in the introduction of this paper, the definition of these concentration levels (suns) is done taking into account the relation between the optical device aperture area and the cell area, that it is known as geometric concentration ratio. This ratio is slightly different from the relation between the incoming irradiation and the effective irradiation on the cell surface, and the reason for that difference is because of the optical device efficiency (η_{op}), that can be defined as the relationship between the sunlight power available at the optical device aperture, and the incident solar power that really falls on the cell surface.

The concentration mechanism is done by lens or mirrors that either refract or reflex the incoming light from the sun on top of the cell receiver surface, and some CPV systems have a second concentration stage, that it is usually known as "secondary optics". Depending on the concentration process, as well as the concentration area, there is a wide range of optical devices configurations that can be used in the implementation of a CPV module [5].

3. Present status of the HCPV efficiency

The overall electric cell efficiency (η_{cell}) can be defined as the ratio between the electric power supplied by the cell (P) and the sun radiation (G_X) falling on top of its surface. Therefore, taking into account the cell area (A_R), efficiency will be:

$$\eta_{\mathrm{cell}} = \frac{P(\mathrm{W})}{G_X(\mathrm{W/m^2}) \cdot A_R(\mathrm{m^2})} \qquad (1)$$

Silicon solar cells that CPV modules are using can reach efficiencies around 27%, while multijunction cells can achieve around 39%.

Fig. 2 shows the evolution in the record efficiency of the Silicon cells and the multijunction ones. In the case of Silicon based cells, since the back-contact cell made by Sinton and Swanson in 1987, which achieved an efficiency of 26.5%, its evolution has barely varied. Unlike the silicon cells, the multijunction ones have undergone an exponential growth in the conversion efficiency as it is emerges from the graphic. These values also depend on the concentration factor and mechanism of focusing the sunlight carried out.

Very recently, in August 2009, a lattice-matched triple-junction solar cell from Spectrolab has achieved a record efficiency of 41.6% at 364 suns. All these record efficiencies have been independently verified by cell measurements, where the last ones have been carried out by the National Renewable Energy Laboratory (NREL) [6–11].

Table 1
Record efficiencies in laboratories tests.

	Effic. (%)	Suns	Manufacturer	Date	Type	Description
1	41,6	364	Spectrolab	2009	GaInP/GaInAs/Ge	Lattice-matched
2	41,1	454	Fraunhofer	2009	GaInP/GaInAs/Ge	Lattice-mismatched
3	40,8	326	NREL	2008	GaInP/GaInAs/GaInAs	Inverted monolithic
4	40,7	240	Spectrolab	2006	GaInP/GaInAs/Ge	Lattice-mismatched
5	37,2	500	Sharp	2005	InGaP/InGaAs/Ge	Lattice-matched

Table 2
Commercial cell efficiencies.

	Effic. (%)	Suns	Manufacturer	Type	Country	Description
1	39	500	Emcore/NREL	Multijunction	USA	www.emcore.com
2	38.5	500	Spectrolab	Multijunction	USA	www.spectrolab.com
3	35	500	Spire	Multijunction	USA	www.spirecorp.com
4	35	300	Azur Space	Multijunction	Germany	www.azurspace.com
5	27	100	Amonix	Silicon	USA	www.amonix.xom

It is very important to differentiate between the efficiencies achieved in a laboratory from those that are available in the commercial market. The primers usually have higher efficiencies values because the quality of the manufacturing process is better, as well as it is more controlled and specific, which it is a factor that raises the cost of the cell. On the other hand, the commercial cells have less efficiency in compensation of a price reduction. In Tables 1 and 2 can be observed these differences among commercial solar cells and those produced in research laboratories.

The efficiencies mentioned above are fully dependent on the concentration factor, increasing its value until a certain concentration level, from which the efficiency decreases, principally because the series resistance limits its performance [12]. In Fig. 3 it is shown the dependence of the concentration ration on the efficiency for different photovoltaic technologies.

This change in concentrator cells efficiency is due to the following:

- The electric current that a solar cell generates is proportional to the irradiance which receives on its surface. There is no existing limit to this law until very high concentrations, which nevertheless are beyond a useful level. The useful range extends until 5000 suns, although the range currently used is between 2 and 1000 suns.
- The voltage of the cells (V_{OC}) increases logarithmically with concentration ratios, causing the efficiency of the cell to increase as well. However, in order to maintain this efficiency rise, a more complex cell design is needed to reduce series resistance and other losses due to the high intensity flux of the new current generated.

As it can be observed in Fig. 4, the efficiency of the cell decreases when the temperature rises, so a very important requirement in order to improve both cell efficiency and reliability, is that the overheating of materials should be avoided while the cells are exposed to high irradiance.

The main effect of an increase in the cell temperature is a reduction of the open-circuit voltage of the cell, which affects the maximum electrical power delivered by the cell and, therefore, the cell efficiency drops. The dependence of cell efficiency and cell temperature (T_c), under a certain concentration level, is usually expressed as:

$$\eta_C = \eta_O - \beta(T_c - T_{\text{ref}}) \tag{2}$$

where η_O is the cell efficiency at the reference temperature (T_{ref}) and β is the temperature coefficient of the efficiency.

Nowadays a new technology is being developed for the manufacture of multi-junction cells, the so-called *inverted metamorphic* (IM). The IM cell is created by growing the structure in an inverted order with comparison to conventional multi-junction solar cell technology. That is, the high band-gap sub-cell is grown in the first place; then, the middle sub-cell is grown followed by the lower one.

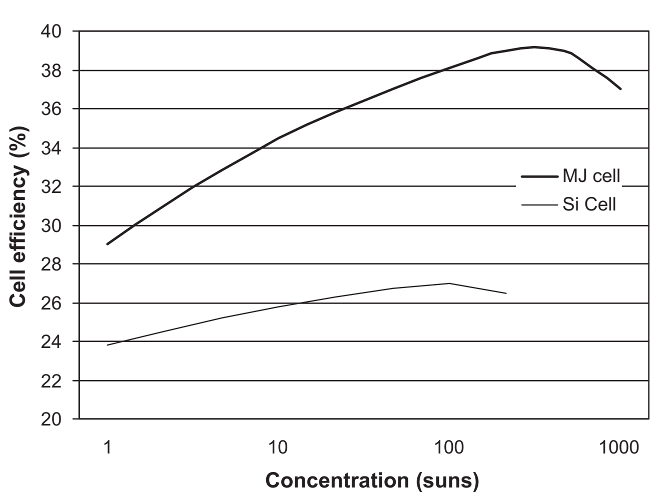

Fig. 3. Typical cell efficiency evolution versus concentration ratio for different technologies.

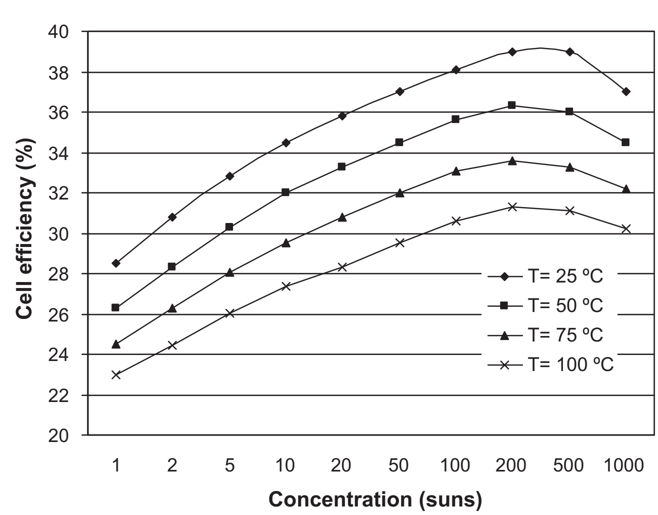

Fig. 4. Differences in the efficiency evolution versus concentration ratio with the multijunction cell temperature.

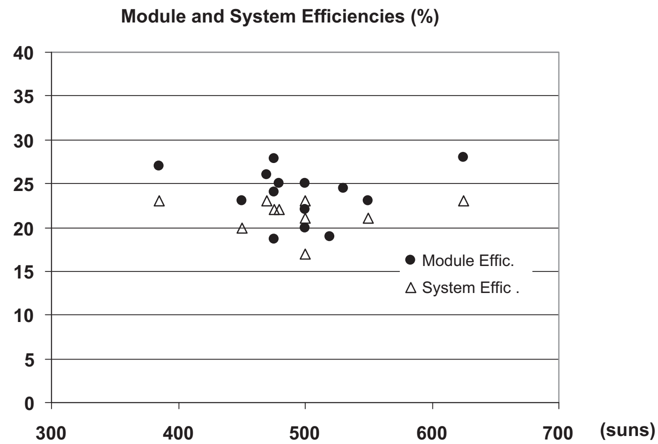

Fig. 5. Module and System efficiencies for different commercial CPV technologies [18–23].

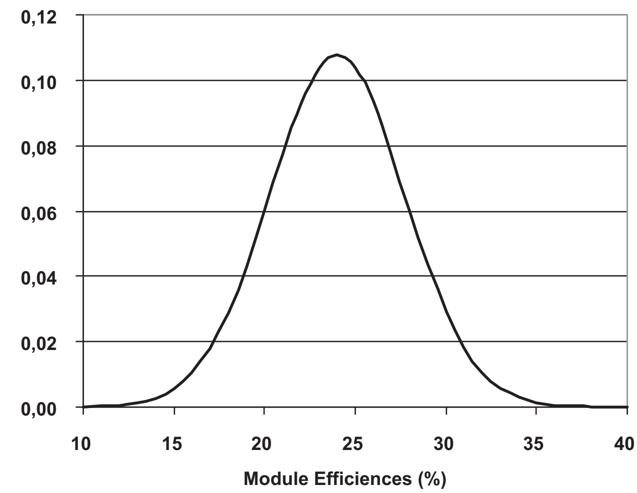

Fig. 6. Probability density function of the module efficiencies.

Finally, the wafer is mounted onto a suitable surface and the original substrate is then removed. This arrangement allows achieving the optimal bandgap combination with improved mitigation of lattice-mismatch-induced growth defects, thus giving improved cell efficiency. One of the main advantages of this new technology is the high efficiency of the manufactured cell. Additionally, the direct mounting of a cell to an arbitrary surface, allows improving the heat loss management, which is a critical factor in CPV systems.

The definition of the module efficiency (η_{mod}) is similar to the one described for the cell, so taking into account the module area (A_M) and an average irradiance on its surface (G_I), efficiency will be:

$$\eta_{\text{mod}} = \frac{P(\text{W})}{G_I(\text{W/m}^2) \cdot A_M(\text{m}^2)} \tag{3}$$

The efficiency of the module (η_{mod}) can also be expressed as a function of the cell efficiency (η_{cell}), the optical efficiency of each cell receiver (η_{op}) and the losses (L) that appear in the module (wiring, mismatch, etc.), so this module efficiency can also be written as:

$$\eta_{\text{mod}} = \eta_{\text{cell}} \cdot \eta_{\text{op}} \cdot (1 - L) \tag{4}$$

As it can be deduced from the previous formula, the energy conversion efficiency of a HCPV module is lower than the one calculated for the cells that make up this module, and it is mainly caused by:

- The serial–parallel association of the cells that gives the module the proper power. The behavior of the cells is not the same among them, mainly caused by slight differences in its manufacturing process. This matter causes the so-called mismatch problem, where the cell with worst quality and performance determines the operational behavior of the rest, therefore decreasing the global efficiency of the module.
- The optical devices also have some losses in the transmission of the incoming light from its surface to the cell area, as it was mentioned previously. It is caused mainly for the non-ideal characteristics of the optical material, which it is ruled by transmittance, absorption and reflection factors, as well as the concentration mechanism chosen. Despite these losses, the present optical technology reaches efficiencies around 85%

These factors cause these differences between cell and module behavior, so the module global efficiency, according to the data provided by manufacturers, goes up to around 20–30%.

The system efficiency is the relationship between the power generated by the system and the incident sunlight energy. The definition of the system efficiency (η_{sys}) is similar to the one described for the module, so taking into account the generator area (A_G) and an average irradiance on its surface (G_I), efficiency will be:

$$\eta_{\text{SYS}} = \frac{P(\text{W})}{G_I(\text{W/m}^2) \cdot A_G(\text{m}^2)} \tag{5}$$

The efficiency of the module (η_{mod}) can also be expressed as a function of the module efficiency (η_{mod}) and the losses (L) in the rest of elements (BOS efficiency), so the system efficiency can also be written as:

$$\eta_{\text{SYS}} = \eta_{\text{mod}} \cdot \eta_{\text{BOS}} \cdot (1 - L) \tag{6}$$

There is barely data from modules and systems efficiencies, because very few of them have been published as the companies are reluctant to give any additional information of their products, apart from the electrical parameters, mainly because they are still gathering operative experience with their new system designs and these data are considered to be strategic and confidential for their commercial purposes. In addition to that, most of the data published are uncompleted, as they do not indicate any of the following information:

- Measuring conditions
- Laboratory of measure
- If the values obtained come from commercial products or prototypes

For such reasons, it only can be indicated that the present concentration module efficiency is located in the range of 20–30%, while the efficiency of the present systems is around 20% as it can be observed in Fig. 5 [13–17].

Although there is scarce experience in this technology, analyzing the module and system efficiencies published by different CPV technologies, it can be observed that the collection of efficiencies in the modules measured, follow a normal distribution with a mean of 24% and a standard deviation (σ) of 4% [18–22]. In Fig. 6 it is shown this distribution.

4. HCPV efficiencies forecast

The efficiency upper limit of multijunction solar cells increases with the number of cells that make the stack. However, the relative rise up in efficiency decreases each time the cell stack is multiplied, because the complexity of the system is higher each time a new cell is added, so in practice it becomes unlikely to have more than 5 or 6

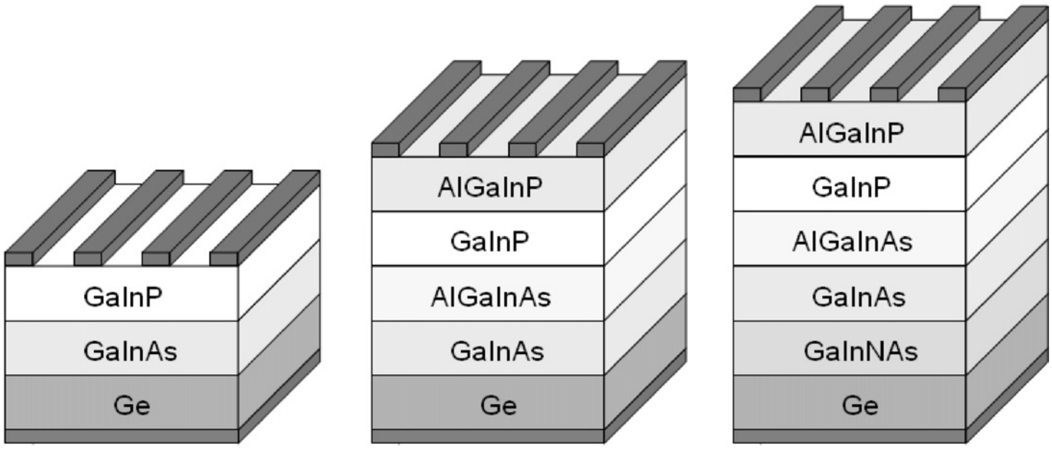

Fig. 7. Scheme of the 3 junction, 5 junction and 6 junction solar cells.

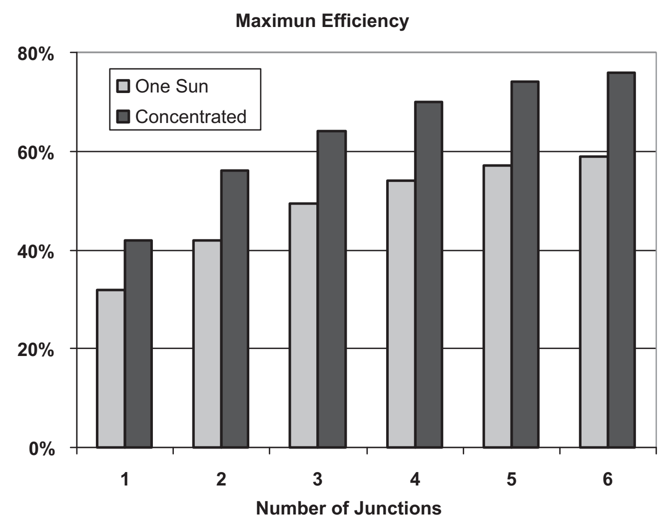

Fig. 8. Theoretical efficiencies as function of the number of junctions.

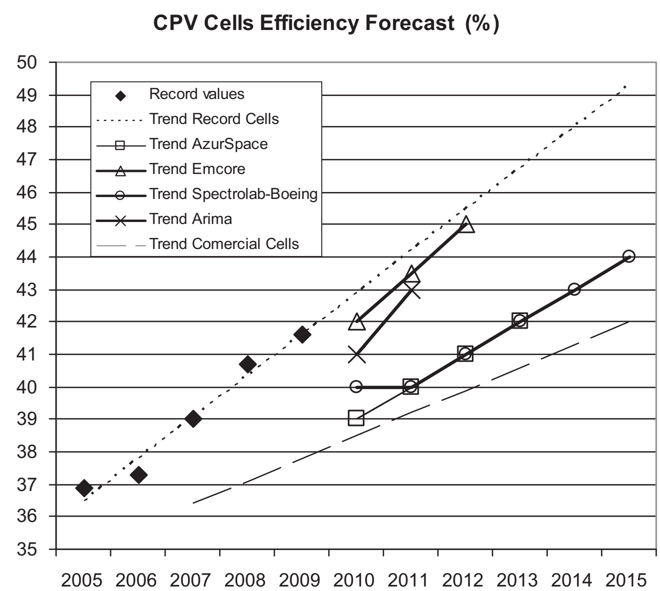

Fig. 9. Forecast of concentrator cell efficiency Improvements towards 2015.

cells in the same stack (see Fig. 7). In Fig. 8 it is shown the upper limit values in the cell efficiencies, considering the theoretical models proposed by different authors, and assuming those light levels that cause higher efficiency [23,24].

It should be remembered that the absolute upper limit of tandem cells, with infinite junctions, is of 86.4% for AM0 spectrum, but even this might not be the highest efficiency for an ideal solar converter, whose upper limit could reach 93.1% [25].

Taking into account the historical evolution of cell efficiency shown in Fig. 2, and the estimations made by CPV manufacturers, the cell efficiency evolution forecast up to 2015 is shown in Fig. 9.

It is very important to mention that the cell efficiency data published by the manufacturers, as well as the forecast values predicted by these companies, do not specify if these data come from record cells, lab's manufactured or commercial cells, so the efficiency evolution forecast shown in Fig. 9, is between the trends of the commercial cells and the record ones.

The potential improvement in the manufacturing process of the CPV elements as well as the new designs that are being accomplished, makes the energy efficiency forecast to have a high learning rate, which means that in the next few years, CPV elements will have a considerable improvement in energy terms.

If the different parts of a CPV system are analyzed, a forecast prediction can be issued. Our prediction is based on an analysis of the state of the art, the historical evolution of PV systems and the commercial target of the manufacturers as well as the analysis of the public institutions involved in the promotion of this technology [26].

Table 3
Present situation and forecast in the efficiencies of the CPV elements.

Efficiency	Present situation (2010)	Forecast (2015)
Cells	30–41%	42–50%
Modules	20–30%	30–40%
Systems	18–25%	26–32%

A short-term efficiency forecast is shown in Table 3, where commercial cells will reach efficiency levels up to 50%, modules around 35% and systems up to 32%, which will imply a substantial reduction of manufacturing costs.

5. Conclusions

High Concentrator PhotoVoltaics technology is still in a deployment stage, but the cells and modules efficiency data offered by their manufacturing companies, as well as the measuring experiments carried out by several research centers, forecast an attractive short-term increment in its efficiency, which means that these sys-

tems could be profitable in economical and energy terms in a short period of time. This fact represents a potential alternative to flat module Photovoltaic systems in the energy generation market.

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